Effect of Cropping Systems on the Structure of the Ploughed Layer : Results of a Long-Term Experiment and Modeling

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Abstract: A field experiment was conducted (1989-1997) in northern France to evaluate the effects of cropping systems on the structure of a loamy soil. Three cropping systems involving different crop rotations (based on winter wheat, pea, rape, maize and sugar beet) and different timetables for cultivation (early or late sowing, early or late harvesting) were studied. Soil structure was evaluated by a morphological analysis of the ploughed layer and defined by the proportion of the soil profile with a massive structure and no visible macropores. Soil compaction, which created the massive zones, occurred mostly during maize and sugar beet harvesting late in the season, in wet conditions. The change in the soil structure over time, i.e. the change in the proportion of massive zones, varied greatly, depending on the cropping system and on the climatic conditions during the year. A model simulating the change in soil structure over time was tested. It has to be improved to better take into account the initial soil structure and the soil loosening during ploughing. It is a useful tool for analyzing the changes in soil structure as a function of cropping systems and so design sustainable tillage systems.

1 Introduction

The soil structure of agricultural fields is subject to frequent changes due to tilling and harvesting. The field operations involve loosening caused by tool action and compaction caused by agricultural machinery wheels. Soil conditions at the time of field operations and machinery characteristics are responsible for the extent of those structural changes. Although it is essential to predict the global effects of cropping systems on soil structure, in order to evaluate their sustainability, there are very few references dealing with these effects. The main reason is the complexity of the interactions between the factors responsible for changes in soil structure in the field. This paper describes an 8-year field experiment (Boizard *et al*., 2002), in which we recorded the changes in the structure of the Ap layer with time, using a method based on a morphological description of the soil structure proposed by Manichon (1987). We will also discuss the perspectives these results offer for modeling the long term effects of cropping systems on soil structure (Roger-Estrade *et al*., 2000).

The method described by Manichon (1987) allows the visual identification of the zones having different degrees of compaction and loosening in a soil profile. Particular attention was paid to the zones having a massive structure and showing no visible macroporosity, i.e. with very low structural porosity. These compacted volumes are created under the wheels of traffic in wet conditions. One major objective of tillage is to reduce these volumes within the Ap layer: they are fragmented and displaced during ploughing and split up during secondary tillage. New compacted zones are created when field operations occur again in wet conditions. The extent of these massive compacted zones within the ploughed layer can therefore be used to quantify the cumulative effects of cropping systems on soil structure.

2 Materials and methods

2.1 Site and soil

The field experiment began in 1989 in northern France (Péronne, 50°N latitude, 3°E longitude, 85 m elevation). Three cropping systems were compared :

- cropping system I. Rotation was pea/winter wheat/rape/winter wheat. Sowing and harvesting were always carried out in summer or early autumn to suit the physiology of the crops involved. Thus they occurred during a dry period of the year, with little risk of soil compaction.

- cropping systems II and III. Rotation was sugar beet/winter wheat/maize/winter wheat. Sowing and harvesting of sugar beet and maize are done in spring and autumn, in quite wet periods of the year with a high risk of soil compaction. Consequently, cropping system II was managed so as to avoid sowing or harvesting in wet conditions to limit the risk of soil compaction. Cropping system III was managed so as to maximize light interception by the sugar beet and maize: sugar beet and maize were sown in early spring and harvested in late autumn, during wet periods of the year, to maximize soil compaction.

Each crop of each cropping system was grown every year, giving 12 treatments. The experimental design consisted of two blocks (total of 24 plots), with a plot area of 0.40 ha. This plot size made it possible to reproduce the patterns of machinery use on commercial farms. No minimum tillage was used, each plot underwent moldboard ploughing (0.30 m depth) every year. The soil was a silt loam (Typic Hapludalf and Luvisol Orthique) with a pH of 7.6 and contained 190 g clay kg^{-1}, 738 g silt kg^{-1}, 50 g sand kg^{-1}, 17 g organic matter kg^{-1} and 5 g $CaCO_3$ kg^{-1}. Soil water content was 0.252 g g^{-1} at –10 kPa and 0.093 g· g^{-1} at –1500 kPa.

2.2 Soil measurements

The location of wheel tracks on the plot was recorded after each operation. The soil water content of each plot was measured gravimatically before each tillage and harvest operation. The structure of the soil was assessed after each crop sowing by the method of Manichon (1987) by mapping typical macroscopic structural features on the vertical face of a 3 m wide soil profile for each plot (Fig. 1). The areas with a massive structure and no visible macropores were determined visually on the soil profiles. These zones, called Δ zones, resulted from the greatest soil compaction in field conditions. The soil profile was photographed and the pictures were digitized for image analysis. The soil profile was divided into zones, defined by the presence and the origin of the tractor wheel tracks. Image analysis was used to quantify the effect of cropping systems on soil structure, by evaluating 2 criteria:

- the compaction due to field traffic during the year of the observation (short term effect of the cropping system) was evaluated as the proportion of Δ zones located under the wheel tracks (Richard *et al.*, 1995).
- the cumulative (long term) effect of cropping systems on soil structure was expressed as the proportion of Δ zones located outside the part of the profile wheeled after the last ploughing date (Δ zones inherited from the preceding crops).

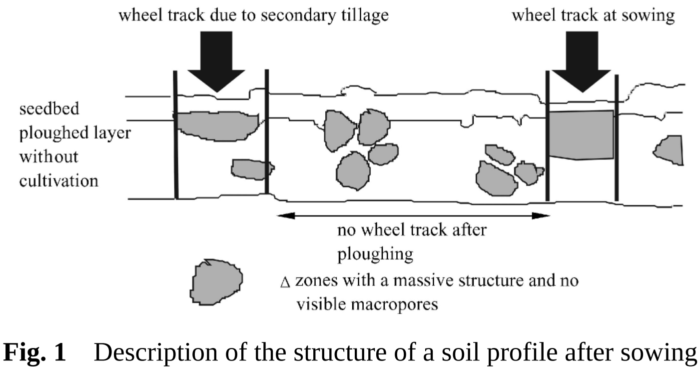


Fig. 1 Description of the structure of a soil profile after sowing

2.3 Model

The model simulates the change over several years in the Δ zones within a soil profile . The depth of the soil profile is the deepest tillage depth (about 40 cm), soil profile width is several meters to take into account the different wheel tracks within the farmer's field due to cultivation. The soil profile is divided into elementary 1 cm by 1 cm plots. Each square plot has or has not a Δ structure. The model calculates the change in the structure (Δ or not Δ) of each square plot during soil compaction under wheel tracks and during superficial tillage in the tilled layer. It calculates the change in the distribution of the Δ zones within the soil profile due to ploughing, which causes lateral soil displacement. The model thus calculates the change in the proportion of the Δ zones within the ploughed layer for several years, after each operation involved in a given cropping system. It provides a map of the structure of the ploughed layer at each step.

The location of each wheel track is calculated from the geometry of the tractive machinery and their tools. The width and the depth of the Δ zones created under each wheel track during each passage are calculated as a function of the equipment characteristics and the soil water content. Three kinds of operations are identified : harvesting with heavy machines, tillage or traffic with wide tires (for example during seed bed preparation), tillage or traffic with narrow tires (for example during sugar beet sowing). The Δ zones disappear during superficial tillage because the soil is loosened. This should create fine earth to a depth equal to the tillage depth (for example, about 5 cm for superficial tillage before sugar beet sowing). The lateral soil movement of each square plot during ploughing is calculated as a function of the ploughing depth and the furrow width.

3 Results and discussion

3.1 Soil compaction due to soil traffic

Fig. 2 shows the percentage of Δ areas under wheel tracks as a function of the soil water content at the time of field operations. The soil water content at the time of field operations varied considerably. The percentage of Δ areas increased with soil moisture and depended on the characteristics of the equipment used. Seed bed preparation with wide tyre and low inflation pressure (70 kPa) generated no Δ zones due to wheel compaction unless the soil water content was very high. In contrast, sowing with narrow tyres and low load and harvesting with wide tyres and heavy load, resulted in Δzones over a wide range of moisture conditions.

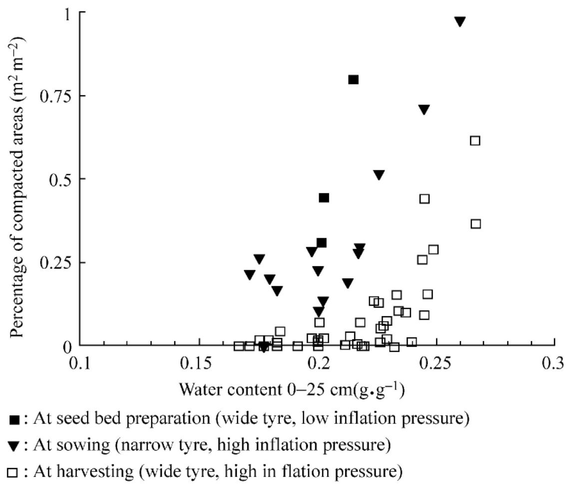
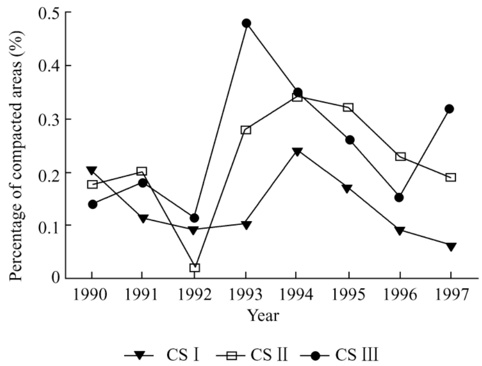


Fig. 2 Percentage area of the cultivated profile under wheel tracks that had massive structure and no visible macropores under wheel tracks (Δ zones) versus soil water content at the field operation

3.2 Cumulative effects of cropping systems

Fig. 3 shows the changes in the proportion of Δ zones for the three cropping systems evaluated within 3 plots which were always under winter wheat in the same year. At the beginning of the experiment (in 1989), the initial percentage of Δ areas was about 20%. The proportion of Δ areas fluctuated greatly, depending on the cropping system and on the climatic conditions of the year. System I, pea/winter wheat/rape/winter wheat, with sowing and harvesting carried out in dry conditions, generated few compacted zones. The proportion of Δ areas was higher from 1993 in systems II and III, based on the crop rotation sugar beet/winter wheat/maize/winter wheat. The autumn of 1993 was very wet, and maize harvesting and sugar beet uprooting caused the formation of Δ zones. The proportion of the soil surface affected by wheel tracks during sugar beet uprooting was also very high. In the 3 cropping systems, the decrease in the percentage of Δ areas could be rapid (Fig. 3). The percentage of Δ areas decreased because fewer new Δ areas were formed than those removed by tillage. A model is need to understand the balance between the formation and loss of Δ areas. The percentage of Δ areas in system III increased again in 1997 after sugar beet uprooting.



	1990	1991	1992	1993	1994	1995	1996	1997
CS I	Pea	Wheat	Rape	Wheat	Pea	Wheat	Rape	Wheat
CS II	Sugar beet	Wheat	Maize	Wheat	Sugar beet	Wheat	Maize	Wheat
CS III	Maize	Wheat	Sugar beet	Wheat	Maize	Wheat	Sugar beet	Wheat

Fig. 3 The change in the percentage of compacted areas (Δ zones) in the ploughed layer over time for three plots of each cropping systems (CS). The soil profile was always examined after sowing of each crop. Only the zones outside the wheel tracks from the last sowing were taken into account when calculating the percentage of Δ areas

3.3 Results of the simulation

An example of the results given by the model of Roger-Estrade *et al.* (2000) is given in Fig. 4 for cropping system III. The percentage of Δ zones in the whole ploughed layer was calculated after each field operation. The model gave good predictions of the increase in the percentage of Δ areas after sugar beet uprooting and wheat sowing in autumn 1993. The model gave a good indication of the later trend to a decrease in the percentage of Δ areas and the increase in 1997. But the percentage of Δ areas was always overestimated. The Δ zones only disappeared from the soil layer tilled during seed bed preparation in the model, while they may also disappear during ploughing if it is not done in too wet conditions.

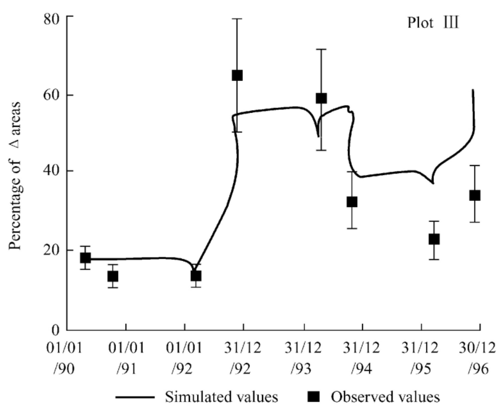


Fig. 4 Change in calculated and observed percentages of compacted zones in the whole ploughed layer for cropping system III

4 Conclusion

The cropping system has major effects on the change in the structure of the ploughed layer. We find that soil compaction occurred mainly during harvesting in wet conditions, because of the high pressure applied on the soil surface due to heavy axle loads. In contrast, very little soil compaction was produced by seed bed preparation, which involved lower axle loads and wide tyres. These results are consistent with those of other studies (Soane *et al*., 1980/1981; Hakansson, 1988). The change in the soil structure over time varied greatly, depending on the cropping system and on the year. The highly compacted zones created during harvesting in wet conditions can quickly disappear from the ploughed layer. Moldboard ploughing, which lifts the volumes of compacted soils to near the soil surface, where they are loosened and weathered, is of particular importance. The model we used gave the general trend of the change in soil structure over time. It is already a useful tool for analyzing the change in soil structure as a function of the cropping system, in order to design sustainable tillage system. In particular, it can be used to evaluate the effect of minimum tillage, which can cause great changes in soil structure when there is severe soil compaction during harvesting.

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